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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 : H02K 41/03

A1

(11) International Publication Number: WO 94/26020

(43) International Publication Date: 10 November 1994 (10.11.94)

(21) International Application Number: PCT/GB94/00906

(22) International Filing Date: 28 April 1994 (28.04.94)

(30) Priority Data:
9308841.7 29 April 1993 (29.04.93) GB

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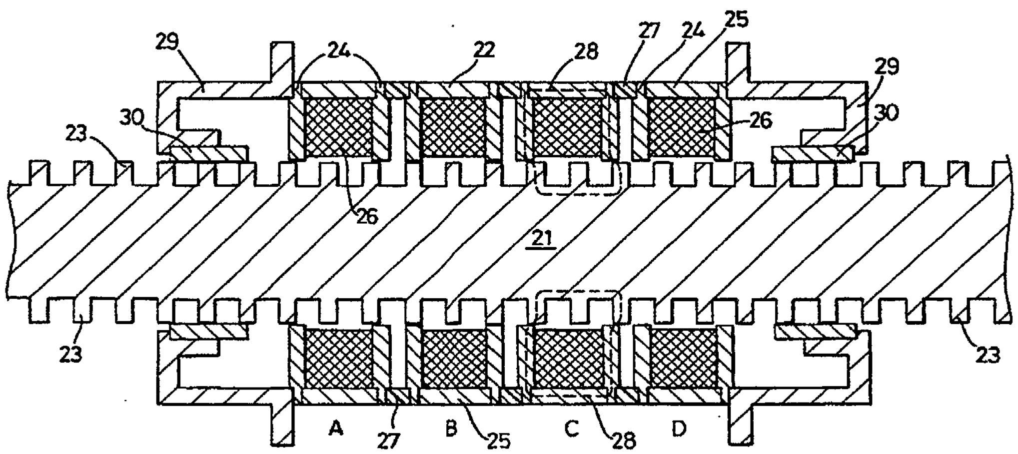
(81) Designated States: AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, ES, FI, GB, GE, HU, JP, KG, KP, KR, KZ, LK, LU, LV, MD, MG, MN, MW, NL, NO, NZ, PL, PT, RO, RU, SD, SE, SI, SK, TJ, TT, UA, US, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

**Published**
*With international search report.*

(54) Title: LINEAR ACTUATOR




**(57) Abstract**

A linear actuator is disclosed comprising an inner mover (21) and an outer stator (22). The mover (21) is a solid ferromagnetic cylinder having transverse slots cut in its outer surface which define a number of magnetic poles (23) facing outwardly towards the stator (22). The stator (22) is made up of four identical component sets, (A, B, C and D). Each set comprises a core formed from two ferromagnetic discs (24) positioned to either side of a ferromagnetic ring (25), and a cylindrical solenoidal coil (26). Each component set is separated from adjacent sets by means of brass spacing rings (27). When a respective stator pole is excited, the magnetic flux circuit is closed and substantially independent from the other component sets. The actuator includes two stator end shields (29), and bearings (30) between the open ends of the end shields (29) and mover (21).

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# LINEAR ACTUATOR

## Field of the Invention

This invention relates to a linear actuator, of the type for use in producing, from electrical energy, linear movement in any component to which it is connected. The invention also provides certain components for use as parts of such an actuator.

## Background to the Invention

Actuators are well known devices used to impart movement, on demand, to mechanical components such as switches, levers and the like. They may be of the rotary or the linear type, depending on the type of movement they produce. Originally, actuators were mechanically driven (for instance, pneumatically or hydraulically). Later versions, however, have made use of electrical energy in order to produce the desired movement.

Recently, considerable interest has been shown in direct linear electrical actuators, in particular to produce precise linear motion over a limited displacement range. Such actuators covert electrical energy directly into kinetic energy of linear motion, thus avoiding the backlash and hysteresis effects which can occur when mechanical interfaces are used for instance to transform the rotation generated by an electrical motor into linear motion. Unlike conventional mechanical actuators, based on pneumatic or hydraulic systems and producing a high force per unit mass, a direct linear electrical actuator does not require auxiliary components such as compressors, pumps, special pipes and valves, etc and is also more attractive from an environmental point of view. It makes possible a greater degree of control and precision than could be achieved using mechanical actuators.

Developments in electronic circuitry, and in particular control systems, have contributed to the increasing

interest in direct linear electrical actuators. Many such developments have now been introduced into rotary-type actuators. However, their incorporation into the linear counterparts of the rotary actuators has been less easy, since, as is usually the case with linear electrical machines, the constraints associated with the linear construction impose considerable limitations on the ranges of operating velocity and displacement achievable.

One example of an electrically controlled rotary actuator, developed in the last two decades, is the "switched reluctance" drive assembly [1]. This was originally developed in the form of a rotary drive motor. It includes a circular stationary component (the "stator"), circumferentially surrounding a rotatable component (the "rotor") which is itself connected to a mechanical component to which movement is to be imparted. Both the rotor and the stator include a series of radially facing magnetic poles. Operation of the device is based on the "variable-reluctance" principle, ie when the stator poles are excited, the rotor poles tend to try to align with the stator poles. Provided that the rotor and stator poles are appropriately positioned, and the stator poles excited in an appropriate sequence, the electromagnetic forces produce a torque which causes the rotor to rotate. In its simplest form, the device produces a stepped movement, as each pole of the rotor in turn aligns itself with a corresponding stator pole. However, this stepped movement may be converted to a continuous movement by the inclusion in the device of suitable position or movement sensors and feedback controls.

Since the introduction of the switched reluctance drive assembly, research into its operation has yielded encouraging results. It is also much simpler in construction than earlier devices, either DC or AC controlled.

The switched reluctance rotary drive has since been developed into a linear equivalent. In [2], the potential of the linear switched reluctance motor as a low speed drive is investigated; it is reported that the drive allows precise speed- and position-controlled linear motion at low speeds. This contrasts with linear synchronous and induction drives, which have serious design limitations in terms of the magnetic pole pitch and the operating frequencies available in low speed applications.

Essentially, the linear switched reluctance motor described in [2] is no more than an "unwound" version of the rotary drive assembly. Thus, the circular stator becomes a linear array of magnetic poles and the rotor a second linear array arranged to face the first and to move parallel thereto. Movement of the "rotor" relative to the stator is caused by the tangential forces which tend to align the "rotor" poles with the excited poles of the stator.

In the rotary drive, the normal component of the force of attraction acting orthogonally between the stator and the rotor pole faces is neutralised by the equal force acting between the diametrically opposite pair of stator and rotor poles. However, in the linear counterpart, these forces can present serious mechanical problems. The problem may in part be overcome by the use of a symmetrically arranged, double-sided, version of the machine; this however is still difficult to construct and cumbersome.

Examples of known linear actuators are described in references [3] and [4]. In reference [5], a linear actuator is described which has a cylindrical configuration. In low speed applications, where because of relatively low eddy current losses the magnetic core does not have to be laminated, a cylindrical configuration gives significant advantages compared to the rectilinear configuration. For instance, the normal forces circumferentially distributed between the moving and stationary parts are neutralised due to the circumferential

symmetry of the cylindrical arrangement. This allows a smaller air gap to be used between the stationary and moving parts, and thereby a better use of active materials. Other advantages include a much simpler bearing structure, self-supporting coils, ease and accuracy of assembly and a better ratio of active to total volume.

However, a cylindrical linear actuator such as that described in [5] is still relatively complex in construction, and because of the arrangement of the magnetic circuit it is inefficient in producing force for a given volume. In [5], the moving part of the actuator described has a relatively complex construction of magnetic and non-magnetic sections arranged in a series, again contributing to the overall complexity of the device. The stator core is also formed of relatively complex shapes; for instance, the stator pole width is not uniform.

A further disadvantage of the actuator described in [5] is that it requires six phases which are grouped in two groups each consisting of three phases. These groups are magnetically uncoupled but the phases within a group are not. If the effect of mutual coupling is to be avoided, only one phase per group can be excited at a time, thereby allowing only one third of the magnetic circuit to be active at any time, ie, the utilisation of the magnetic circuit is relatively low. If two phases per group were excited at a time, the efficiency would be reduced due to the effect of mutual coupling between phases.

It is an aim of the present invention to provide a linear electrical actuator which improves upon known actuators and overcomes or at least mitigates the above described problems. The aim is to provide an actuator which is relatively efficient, compact and of simple and inexpensive construction.

Statements of the Invention

According to a first aspect of the present invention there is provided a linear actuator, comprising a stationary component ("stator") and a moveable component ("mover") and for use in producing, from electrical energy, linear movement of the mover by the variable reluctance principle; the mover and the stator being so arranged that one radially surrounds the other and such that the mover is able to move linearly relative to the stator in a direction parallel to the longitudinal axes of both the mover and the stator; the mover comprising a series of "poles" of a ferromagnetic material arranged along the length of its longitudinal axis and facing radially towards the stator in use; the stator comprising a series of excitable magnetic poles arranged along the length of its longitudinal axis and facing radially towards the mover in use; wherein the stator comprises one or more component sets arranged in sequence and magnetically uncoupled from one another, each component set including two or more excitable magnetic poles, the arrangement being such that for each component set, an independent and closed magnetic flux circuit is formed in use around the poles of the set and an adjacent pole or poles of the mover, when the poles of that component set are excited during use of the actuator.

The construction of such an actuator, where one of the components radially surrounds the other (preferably in an arrangement which is symmetrical about the longitudinal axes of the components, such as a cylindrical arrangement), means that the actuator is relatively easy to construct and also relatively compact.

More importantly, the magnetic independence of each component set of the stator allows an efficient production of force in the actuator. This is because, in a doubly-salient variable reluctance machine which is excited with unidirectional currents, the presence of mutual coupling between phases (represented in this case by the component sets) is undesirable because, at a given current, its

effect reduces the resultant electromagnetic force which causes the motion and thereby also reduces the efficiency of energy conversion. (The use of unidirectional currents for excitation of the phases enables a switching unit used with the actuator to comprise only one switching element per phase, compared with two which would be necessary if bipolar currents were used for excitation.)

The magnetic independence of the component sets also makes possible a high degree of control, since the poles of each component set may be independently excited. Moreover, the use of such independent component sets means that the stator may have a "modular" construction, being easily extended (and hence its force increased) by the addition of further similar component sets.

An actuator in accordance with the present invention does not suffer from the disadvantage mentioned above in connection with reference [5], namely, the need for at least six phases (to avoid the effects of mutual coupling) and for a correspondingly high number of switches and other controls. The actuator of the invention needs only one stator component set (phase) to be operational, although it preferably comprises at least three such sets, in order to be capable of identical performance for two opposing directions of movement of the mover and in order to enable self-starting (see detailed description below). It can make more efficient use of its magnetic circuit than can the actuator described in [5], and yet still avoid the effects of mutual coupling.

Preferably, the stator radially surrounds the mover in use. Ideally, the whole construction is cylindrical in form. The mover, for instance, preferably takes the form of a solid cylinder of an appropriate ferromagnetic material, and the stator of a hollow cylinder within which the mover is able to move. The cylindrical form of the stator may be achieved by the adjacent positioning of several parts, or alternatively the stator may be a single-piece

construction; for instance the stator assembly may be embodied in a non-magnetic tube.

The magnetic poles of the mover preferably take the form of radially facing teeth or similar projections on the outer surface of the mover, provided for instance by the cutting of transverse slots in the surface.

The stator preferably comprises more than one component set, preferably three or more, for the reasons given above. In use, each set may correspond to a different phase of excitation. A convenient number of component sets might, for instance, be four, the four sets having in use four different phases denoted A, B, C and D. The stator could then be extended by the addition of a further four component sets, having the same phases A, B, C and D, to increase the overall force produced by the actuator. Thus, the stator may comprise two or more component sets, the poles of which (having the same phase) are in use excited in phase with one another, these sets being arranged in an appropriate sequence along the length of the stator, conveniently with other sets corresponding to a different excitation phase in use. The essential feature of the present invention is that each component set should be magnetically uncoupled from the others.

The phase of each component set, in use, is something which the user controls by an appropriately timed excitation of the magnetic poles of each set. The actuator of the present invention preferably additionally comprises excitation means, for exciting the magnetic poles of the stator so as to cause the poles of the mover to move in such a direction as to increase alignment of the mover poles with the stator poles and hence produce linear movement of the mover. This excitation means may be conventional in form; for instance, it may comprise a solenoid coil appropriately positioned relative to the pole or poles of a component set, such that the supply of current to the solenoid coil creates a magnetic field in

the poles. The actuator may additionally comprise, or be used in combination with, a current supply for this purpose.

It should be noted that, because of the actuator's radial construction, only one solenoid coil is needed per component set of the stator in order to induce movement, compared to the two coils needed per phase set in a rectilinear actuator of the conventional type.

The actuator preferably additionally comprises control means, for controlling the excitation means so as to excite the stator poles in an appropriate sequence, thus to produce the desired amount of movement of the mover. The control means preferably includes a position sensor, for sensing the position of the mover, and feedback control means whereby the excitation of the stator poles may be adjusted accordingly to ensure that the mover moves as desired. The control means, including such feedback control means and position sensor, may be entirely conventional. It may be entirely automatic in operation, or require a degree of intervention by the user.

The mover is preferably capable of movement in two opposite directions, parallel to its longitudinal axis. The actuator of the invention is preferably adapted for use in producing limited linear displacements; the degree of control and accuracy which it can achieve makes it ideal for use in such situations.

The stator poles may be in the form of separate discs of a suitable ferromagnetic material, having apertures through which the mover may pass in use and each positioned in use adjacent a solenoid coil which is itself preferably surrounded by a further ring of a ferromagnetic material. A single component set might for instance comprise two pole discs, one either side of a solenoid coil. (At least two poles are needed per component set in order to maintain the magnetic independence of each set.) The solenoid coil

would also be connected to the excitation means and control means of the actuator. Each component set is preferably separated from adjacent sets by a spacer, such as a spacing ring made from a non-magnetic material.

Such pole discs can be produced relatively simply by punching, and the stator rings can be obtained for instance from standard metal tubes. This is not the case with the actuator described in reference [5], where the width of the stator poles is not uniform, and means that simplicity of construction is yet another advantage of the present invention over known actuators.

The stator is preferably of a modular construction, such that any desired number of identical or similar component sets may be joined together in series so as to create a stator of a desired overall length. Such a construction allows great versatility of use of the actuator.

The actuator preferably additionally comprises bearings, of conventional design, positioned between the mover and the stator at the open ends of the latter, so as to ease the passage of the mover into and out of the open ends of the stator during use.

According to a second aspect of the present invention there is provided a stator for use as part of an actuator in accordance with the first aspect of the invention. As described above, the stator will comprise one or more component sets, each magnetically uncoupled from the others. The stator is preferably of such a size and shape as to be able to accommodate a moving component within it in use, more preferably in the form of a hollow cylinder. It is also conveniently of a modular construction, such that its length may be varied according to the number of component sets which it comprises.

According to a third aspect of the present invention there is provided a moveable component for use as part of an

actuator in accordance with the first aspect of the invention. This moveable component preferably takes the form of a solid cylinder of an appropriate ferromagnetic material, the cylinder comprising a series of radially facing magnetic poles arranged along the length of its longitudinal axis.

According to a fourth aspect of the present invention, there is provided a component set for use as part of the stator of an actuator in accordance with the first aspect of the invention, the set including one or more radially facing excitable magnetic poles, preferably of an annular construction. More preferably, the component set is adapted to be connected to an adjacent component set, so as to form part of a series of component sets in an actuator in accordance with the first aspect of the invention.

The present invention will now be described by way of example only and with reference to the accompanying illustrative drawings, of which:

Figure 1 is a schematic cross-section taken through a conventional variable reluctance rotary drive assembly;

Figures 2 and 3 are schematic longitudinal cross-sections taken through two different linear variable reluctance drive assemblies, also of conventional type;

Figure 4 is a schematic transverse cross-section taken through the device shown in Figure 3;

Figure 5 is a schematic longitudinal cross-section taken through an actuator in accordance with the first aspect of the present invention;

Figure 6 is an exploded perspective view of part of the actuator shown in Figure 5;

Figure 7 is a graph showing the variation of phase inductance versus position for the actuator shown in Figures 5 and 6;

Figure 8 is a schematic block diagram of an actuator in accordance with the present invention, including control means; and

Figure 9 is a graph showing the static force characteristics of an actuator in accordance with the invention.

## Detailed Description of the Drawings

Referring firstly to Figure 1, there is shown in schematic cross-section the magnetic circuit of a conventional four-phase variable reluctance rotary drive. The magnetic core of the stator 1 has salient poles labelled (according to their phase) A, A′, B, B′, etc. These poles have solenoidal coils 2; two diametrically opposed coils are connected to form the pole-pair of one phase (for instance, A and A′).

The magnetic core of the rotor 3 also has salient poles 4, but no winding of any kind and no permanent magnet incorporated in it.

Electromagnetic torque, to create movement of the rotor 3, is produced entirely by the variable reluctance principle, ie by the tendency of the rotor poles 4 to align with the stator poles when the latter are excited by the activation of solenoid coils 2. This yields a stepwise rotation of the rotor 3, which may be converted to continuous rotation by connecting the assembly to position sensors and feedback control means.

Shown in Figures 2-4 are the magnetic circuits of linear counterparts to the rotary drive shown in Figure 1. Figure 2 shows a "longitudinally" configured drive assembly comprising a stator 7 having poles A, A′, etc and solenoid coils 8. "Mover" 9 is capable of linear movement in a direction parallel to the longitudinal axis of stator 7. The mover comprises a series of magnetic poles 10 facing towards the poles of stator 7. Essentially, the device shown in Figure 2 is simply an "unwound" version of the four-phase drive shown in Figure 1. The magnetic flux path, shown by means of dotted line 11, in the core of both

the stator and the mover, is seen to be longitudinal with respect to the axis of movement.

The device shown in Figures 3 and 4 has a "transverse" configuration. In this embodiment, the assembly is seen to comprise a mover 13, having a non-magnetic support 14 and a number of magnetic poles 15, and a stator made up of a non-magnetic support 16, a number of magnetic poles 17 and solenoid coils 18. As seen in Figure 4, each of the stator poles is associated with two coils 18. The magnetic flux path, in use, is transverse with respect to the axis of movement of the mover 13 (see dotted line 19).

Mechanically, the longitudinal configuration shown in Figure 2 has advantages over the transverse configuration, being more rigid in construction.

In the devices shown in Figures 2-4, movement of the mover is caused by the tangential force which tends to align the mover poles with excited stator poles. In contrast to the rotary device shown in Figure 1, where the normal forces of attraction between rotor and stator pole faces are neutralised by the same forces acting between diametrically opposite pairs of stator and rotor poles, the normal forces in the linear devices are high and can present serious mechanical problems. These forces can be neutralised to an extent by the provision of a symmetrical, double-sided, version of the linear device, but this is still relatively complex in construction and relatively cumbersome.

The conventional devices shown in Figures 1-4 may be used as, for instance, motors or switch actuators, or in any other situation where movement is to be produced.

Referring now to Figure 5, there is shown in schematic longitudinal cross-section a linear actuator in accordance with the first aspect of the present invention. This comprises an inner mover 21 and a outer stator generally labelled 22. The mover 21 is a solid ferromagnetic

cylinder having transverse slots cut in its outer surface which in turn define a number of magnetic poles 23 facing outwardly towards the stator 22.

The stator 22 is made up of, in this case, four identical component sets, indicated as A, B, C and D. Each set comprises a core formed from two ferromagnetic discs (poles) 24 positioned to either side of a ferromagnetic ring 25, and a cylindrical solenoidal coil 26. Each component set is separated from adjacent sets by means of non-magnetic spacing rings such as 27.

Each component set (or "phase set") is identical to the others, and in theory as many component sets may be arranged together in series as the user desires. The device shown in Figure 5, for instance, comprises four component sets, which in use will be excited at four different phases denoted A, B, C and D (ie, adjacent sets out of phase with one another). To extend the length of the stator, further component sets may be added. For instance, a further four sets might be added, having phases A, B, C and D, thus providing two component sets for each phase. This multiplies the overall force which the actuator is able to supply.

In the device of Figure 5, movement of the mover 21, linearly with respect to stator 22, is caused in the same way as described with reference to the devices of Figures 2-4. The mover poles 23 move so as to increase their alignment with those stator poles 24 which are excited at any particular time; an appropriate sequence of excitations causes the required degree of linear movement. In Figure 5 there is shown, by means of dotted lines 28, the magnetic flux circuit generated when, in use, the poles of phase set C are excited. The circuit is closed and substantially independent from the other component sets. It should be noted that the difference between the mover and stator lengths determines the maximum linear displacement achievable.

The actuator shown in Figure 5 includes two stator end shields 29, and bearings 30 between the open ends of the end shields 29 and mover 21.

Figure 6 shows in more detail the construction of the stator components of the actuator shown in Figure 5. It can be seen that the stator can be made up of as many component sets as the user wishes to place adjacent one another. It can also be seen in Figure 6 that bolts 31 are used to secure the stator components together between the two end shields 29.

From a mechanical point of view, the actuator shown in Figures 5 and 6 has a number of advantages over conventional actuators:

1. Convenience of manufacturing - the actuator construction is based on elements having simple shapes. For instance, the mover slots may be machined from a solid cylindrical block. Alternatively, ferromagnetic rings may be provided around the mover shaft in order to create the necessary sequence of magnetic poles, or a series of non-magnetic rings, made of a material having high electrical resistivity, may be included on the outer surface of a ferromagnetic shaft, in order to mimic the slot spacings shown in Figure 5.

2. Convenience of assembly - as shown in Figure 6, the edges of the magnetic discs and other components are machined so as to allow their precise alignment. Bolts 31 are used to tighten the complete assembly. Alternatively, the stator assembly may be located in a non-magnetic housing, such as a tube, to simplify its assembly.

3. Convenience of extension - as described above, the force provided by the actuator may be increased simply

by the addition of further component sets to the stator.

The principle of operation of the actuator shown in Figures 5 and 6 is as follows. As shown by the dotted lines 28 in Figure 5, each component set of the stator 22 forms an independent magnetic circuit, ie all sets, regardless of their phase, are magnetically uncoupled. This fact is important in order to maximise the available force in a variable reluctance doubly-salient structure such as that shown in Figure 5 (when excited by unidirectional currents), and also allows a high degree of control and flexibility.

The force which produces movement of mover 21 is produced by the reluctance principle, ie by the tendency of the mover poles 23 to try to align with excited stator poles 24. Thus, when one of the component sets is excited, a force is produced between the stator and the mover at positions in which there is a tendency for the phase inductance to change, ie where the derivative dL/dx is not zero. The direction of this force depends exclusively on the sign of the derivative dL/dx. The fact that the force is independent of the direction of current flow allows the use of unidirectional currents for excitation of the magnetic poles; thus, relatively simple electronic switching circuits may be used with the actuator.

Figure 7 shows the idealised phase inductance (L) variation with mover position for an actuator in accordance with the present invention. The variation is idealised in the sense that the fringing effect of magnetic field and the magnetic saturation are neglected. One length of the cycle ($\lambda$) is equal to the mover pitch consisting of a "tooth and slot" pair (length: tooth + slot = t+s). In the configuration of Figure 5 the stator pole (disc) width is equal to the mover pole (tooth) width. (These two can be different, in which case there would be a flat part in the region of maximum inductance in Figure 7).

The positions $x_1$-$x_4$ on the graph correspond to the following:

$x_1$ is the position where the leading edge of the mover tooth is aligned with the front edge of the stator disc of the considered phase;

$x_2$ is the position where the axis of the mover teeth is aligned with the axis of the stator disc of the considered phase;

$x_3$ is the position where the trailing edge of the mover tooth is aligned with the rear edge of the stator disc of the considered phase; and

$x_4$ is the position where the leading edge of the next mover tooth is aligned with the front edge of the stator disc of the considered phase. This position is equivalent to position $x_1$, ie $x_4=x_1+\lambda$.

The following regions of the graph can be recognised:

$x_1$-$x_2$: the region where the leading edge of the mover tooth is under the stator disc (the rising region; dL/dx is positive);

$x_2$-$x_3$: the region where the trailing edge of the mover tooth is under the stator disc (the falling region; dL/dx is negative);

$x_3$-$x_4$: the region where no part of the mover tooth is under the stator disc (the minimum inductance region; dL/dx is zero).

The waveforms of inductance variations of adjacent phases are shifted for a quarter of the mover pitch ($\lambda/4$). The requirement for self-starting implies that the magnetic configuration is designed so that at any position at least one phase has dL/dx positive, ie, the stator pole width (t) of a four-phase actuator must be greater than a quarter of the mover pitch ($\lambda/4$).

Referring to Figures 5 and 7, if the phases are excited in the sequence ...A,D,C,B... over the regions of rising

inductances, the motoring operation in the positive (left-to-right) direction of motion will occur. For regenerative braking in the positive direction of motion to take place, the phases must be excited in unchanged sequence over the regions of falling inductances. The sequence ...C,D,A,B... corresponds to the negative (right-to-left) direction of motion.

The actuator of Figure 5 can fulfil the function of discrete positioning (with the step equal to a quarter of the mover pitch length) due to the ability of self-holding without closed-loop position control. By exciting each of the four phases with a series of pulses of a given fixed frequency, where the pulses corresponding to adjacent phases are shifted for a quarter of a period, the actuator can be made to operate as a linear stepper. The resolution of this step-wise motion may be improved by arranging for each of the stator poles to be sub-divided into a number of equidistant sub-poles. The mover may then be modified so that its poles are spaced by the distance between sub-poles of the stator. Some modification of the spacing between stator sets will also be required to preserve the four phases.

The actuator of Figures 5 and 6 is of course controlled by appropriate control means (not shown in the figures), conveniently electronic and of any conventional type. If it is desired to produce continuous motion of the mover 21 rather that stepped motion, a position sensor is needed, to sense the linear position of the mover 21, and also feedback control means to ensure appropriately timed activation of the component sets of the stator depending on the mover position. Thus, the feedback control means enables each phase to be energised during the appropriate interval with respect to the phase inductance variation with mover position.

The position sensor has to be capable of identifying the positions of excitation for each phase, and also of

enabling self-starting. The term "self-starting" is used to express a capability of the actuator to start motion (ie to produce a force) in a desired direction from any position without auxiliary means. The conditions for self-starting are:

(i) At any position at least one phase must have a positive gradient of inductance variation with respect to the increase of the position coordinate in the desired direction. (This is provided by the appropriate magnetic circuit geometry.)

(ii) Each phase must be excited for at least the region $\lambda/q$ ($\lambda$ denotes the mover pitch, and q denotes the number of phases) when the corresponding value $dL/dx$ is positive. (This is provided by the appropriate position detector.)

Figure 8 shows schematically how the actuator of Figures 5 and 6, generally labelled 35, may be combined with appropriate control means. The mover 36 is capable of movement in two opposing directions as shown by the arrows. Sensor 37 detects the position of mover 36 and signals the logic control unit 38 accordingly. Other controls are input into this unit, as indicated at 39, either by other control means such as a computer and/or by the user. The logic control unit, on the basis of all input information and controls, then instructs the switching unit 40, which in turn controls the supply of power to the stator of the actuator 35. In this way, the longitudinal position of mover 36 determines when, and in what sequence, the stator poles are excited so as to induce the necessary further movement. The controls shown schematically in Figure 8 may be of purely conventional design.

A system such as that shown in Figure 8 allows the user to achieve greater accuracy of movement by means of an actuator in accordance with the invention. The power supply shown in Figure 8 supplies DC current to the switching unit. The switching topologies and logic-

controlled circuitry used in conventional rotary switched reluctance drives are equally of use in actuators according to the present invention.

Overall, then, control of the actuator movement is achieved via (1) the voltage or current fed to the component sets and (2) the switch-on and switch-off positions. Again, control strategies used in conventional rotary drives may be used in an actuator according to the invention.

A good indication of the potential of an actuator is the "measured static force characteristic" and in particular the performance parameter "force per unit active volume". Such characteristics were investigated for an actuator such as that shown in Figure 5, having an active stator length of 106.5 mm, an outer stator core diameter of 80 mm, an inner stator core diameter of 40.4 mm and an outer mover diameter of 40 mm. Figure 9 shows the measured static force characteristics of such an actuator, when two phases are excited simultaneously (CD, BC, AB, DA) with constant currents. The average values of the static force at three different current values (2.8A, 2.4A and 2.0A) are indicated by the broken lines.

The force can be seen to vary cyclically with the mover position. The zero reference position corresponds to that in which the mover teeth are aligned with the stator discs of Phase A (ie, the position $x_2$ of Phase A); 2.5mm is the position when the mover teeth are aligned with the stator discs of Phase D (ie, the position $x_2$ of Phase D); 5mm is the position where the mover teeth are aligned with the stator discs of Phase C (ie, the position $x_2$ of Phase C); 7.5mm is the position where the mover teeth are aligned with the stator discs of Phase B (ie, the position $x_2$ of Phase B) and 10mm is the same as the zero reference position.

The force represented in Figure 9 is that produced by the simultaneous action of two phases excited by constant

currents according to the pattern CD, BC, AB, DA. Thus, in the position region from 0 to 2.5mm the phases C and D are excited, from 2.5 to 5mm the phases B and C are excited, from 5 to 7.5mm the phases A and B are excited and from 7.5 to 10mm the phases D and A are excited.

The results in Figure 9 show that, at a current of 2.8A, the average static force is 132N which corresponds to a "force/active volume" ratio of 248 x $10^3$ $N/m^3$. Thus, compared to a known linear cylindrical actuator such as that reported in reference [5], an actuator in accordance with the present invention can have more than twice the "force/active volume" ratio.

It can be seen from the above that an actuator in accordance with the invention is especially useful for generating controlled, low-speed, linear motion. It is smooth and accurate in operation, and also more efficient compared to known actuators. Moreover, it is relatively simple and inexpensive both to produce and to assemble. No permanent magnets are needed, and the absence of brushes means that the actuator is particularly suitable for use in hazardous environments. Conventional controls may be used in association with the actuator.

Most importantly, the incorporation of simple and magnetically uncoupled stator component sets makes the actuator extremely versatile in use and efficient in producing the force necessary to induce movement.

Finally, the mover is of a simple, unitary, construction, which again represents an advantage over certain conventional actuators, such as that described in reference [5].

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CLAIMS

1. A linear actuator comprising a stationary component ("stator") and a moveable component ("mover") and for use in producing, from electrical energy, linear movement of the mover by the variable reluctance principle; the mover and the stator being so arranged that one radially surrounds the other and such that the mover is able to move linearly relative to the stator in a direction parallel to the longitudinal axes of both the mover and the stator; the mover comprising a series of "poles" of a ferromagnetic material arranged along the length of its longitudinal axis and facing radially towards the stator in use; the stator comprising a series of excitable magnetic poles arranged along the length of its longitudinal axis and facing radially towards the mover in use; wherein the stator comprises one or more component sets arranged in sequence and magnetically uncoupled from one another, each component set including two or more excitable magnetic poles, the arrangement being such that for each component set, an independent and closed magnetic flux circuit is formed in use around the poles of the set and an adjacent pole or poles of the mover, when the poles of that component set are excited during use of the actuator.

2. An actuator according to claim 1 in which the magnetic poles of the mover take the form of radially facing projections on the outer surface of the mover.

3. An actuator according to claim 1 or claim 2 which is so arranged that the poles of two or more component sets are in use excited in phase with one another.

4. An actuator according to any preceding claim additionally comprising excitation means for exciting the magnetic poles of the stator so as to cause the poles of the mover to move in such a direction as to

increase alignment of the mover poles with the stator poles and hence produce linear movement of the mover.

5. An actuator according to claim 4 in which the excitation means comprises a solenoid coil appropriately positioned relative to the pole or poles of a component set, such that the supply of current to the solenoid coil creates a magnetic field in the poles.

6. An actuator according to claim 5 in which the excitation means comprises only one solenoid coil per component set of the stator.

7. An actuator according to any preceding claim in additionally comprising control means for controlling the excitation means so as to excite the stator poles in an appropriate sequence.

8. An actuator according to claim 7 in which the control means includes a position sensor for sensing the position of the mover, and feedback control means for adjusting the excitation of the stator poles.

9. An actuator according to any preceding claim in which the stator poles are in the form of separate discs of ferromagnetic material, having apertures through which the mover may pass.

10. An actuator according to claim 9 in which each component set comprises two pole discs, one either side of a solenoid coil.

11. An actuator according to claim 10 in which each component set is separated from adjacent sets by a spacer.

12. An actuator according to any preceding claim in which each stator pole is sub-divided into two or more equidistant sub-poles.

13. An actuator according to any one of claims 9-11 in which each stator pole is sub-divided into two or more equidistant sub-poles by means of at least one circumferential groove on each pole disc.

14. An actuator according to any preceding claim in which the stator is of a modular construction.

15. An actuator according to any preceding claim additionally comprising bearings positioned between the mover and the stator at the open ends of the latter.

16. A stator for use as part of an actuator according to any preceding claim.

17. A moveable component for use as part of an actuator according to any preceding claim.

18. A component set for use as part of a stator according to claim 16, the set including one or more radially facing excitable magnetic poles.

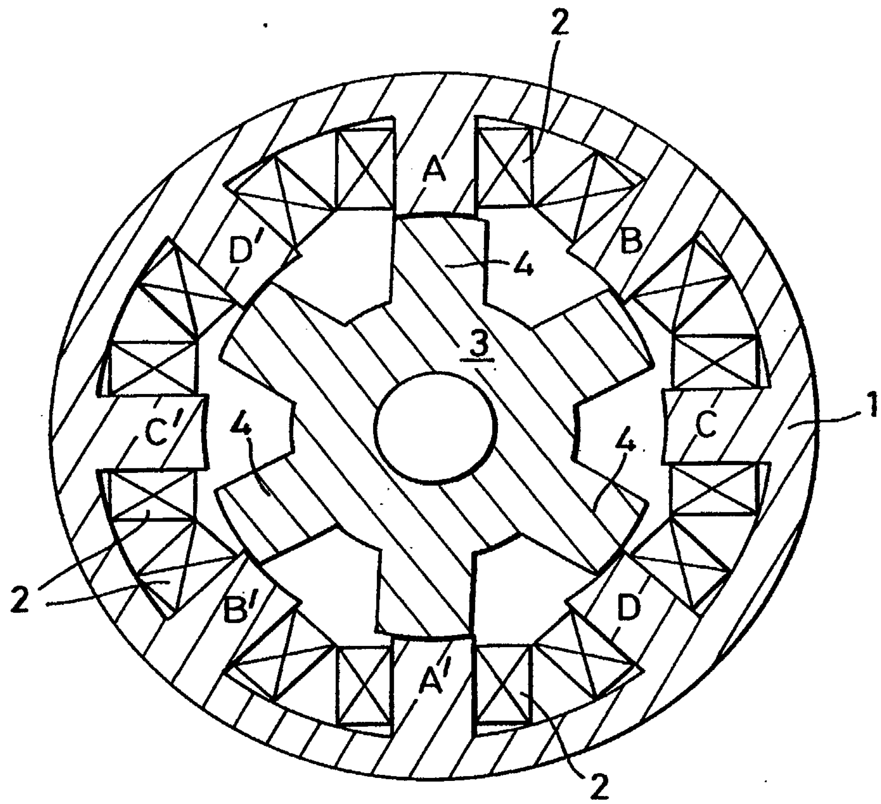



Fig. 1

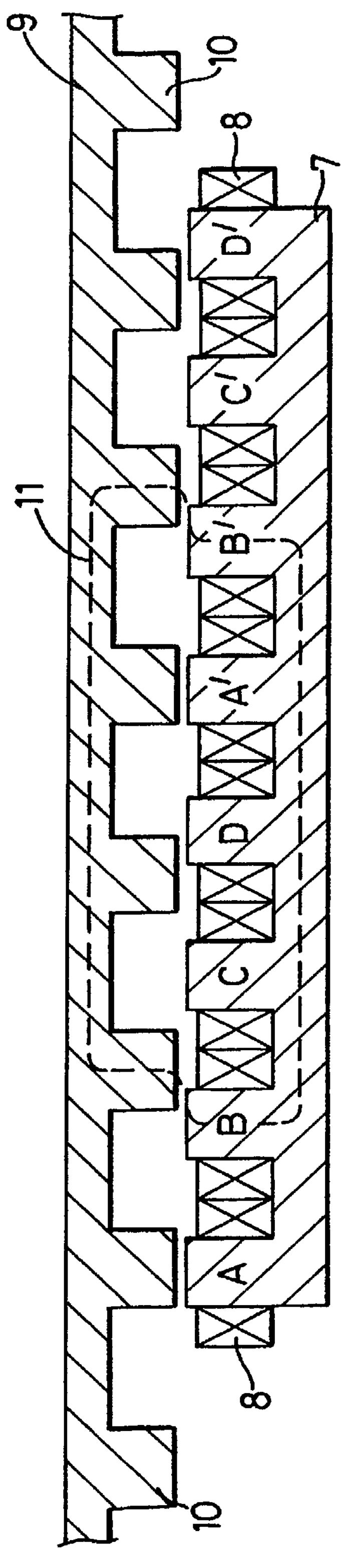



Fig. 2

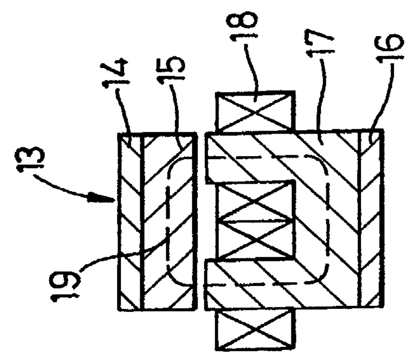



Fig. 4

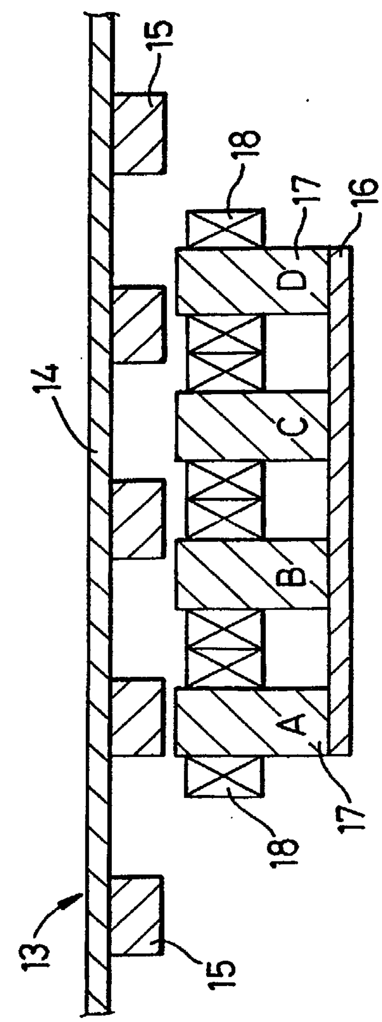



Fig. 3

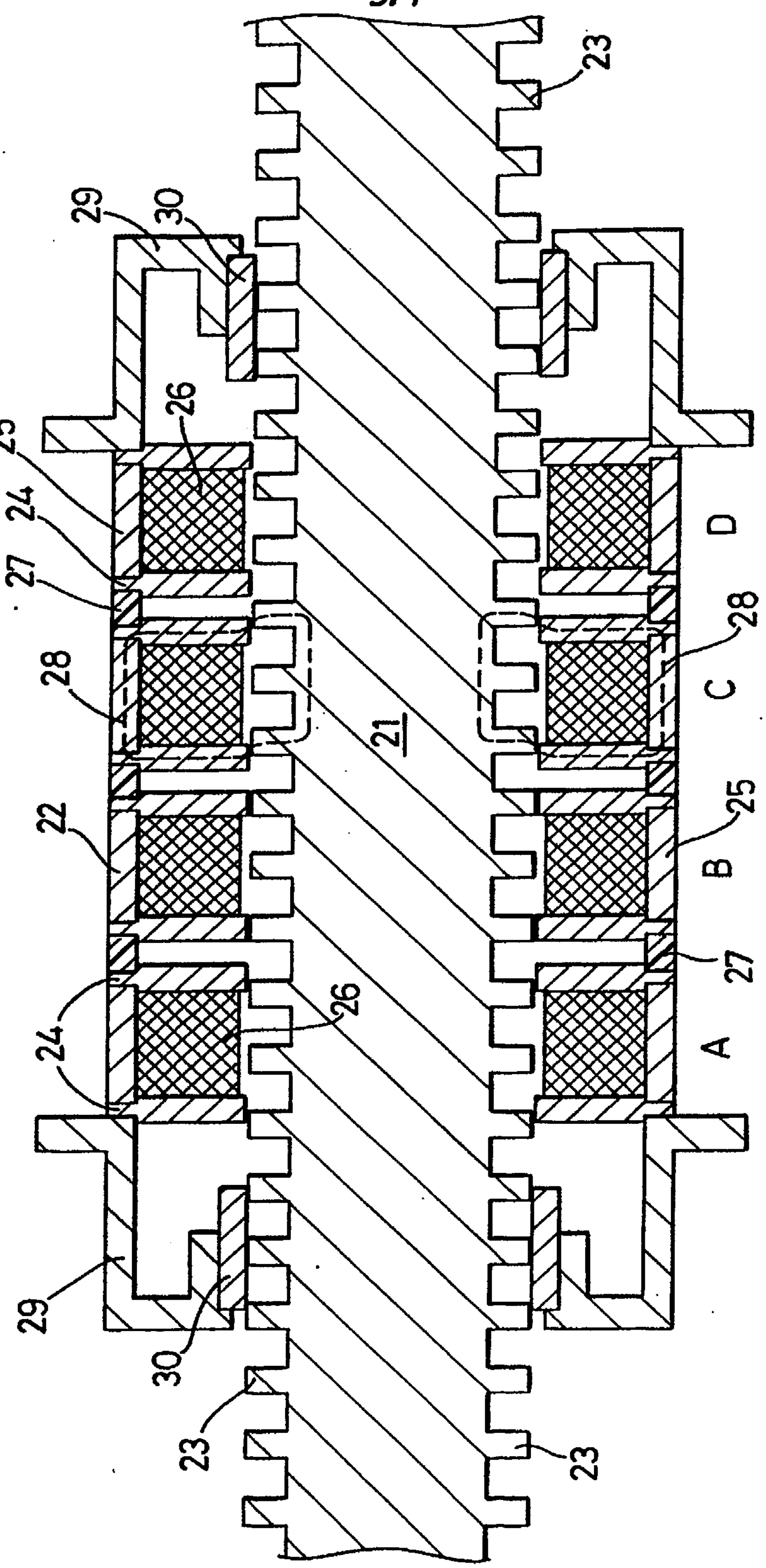



Fig. 5

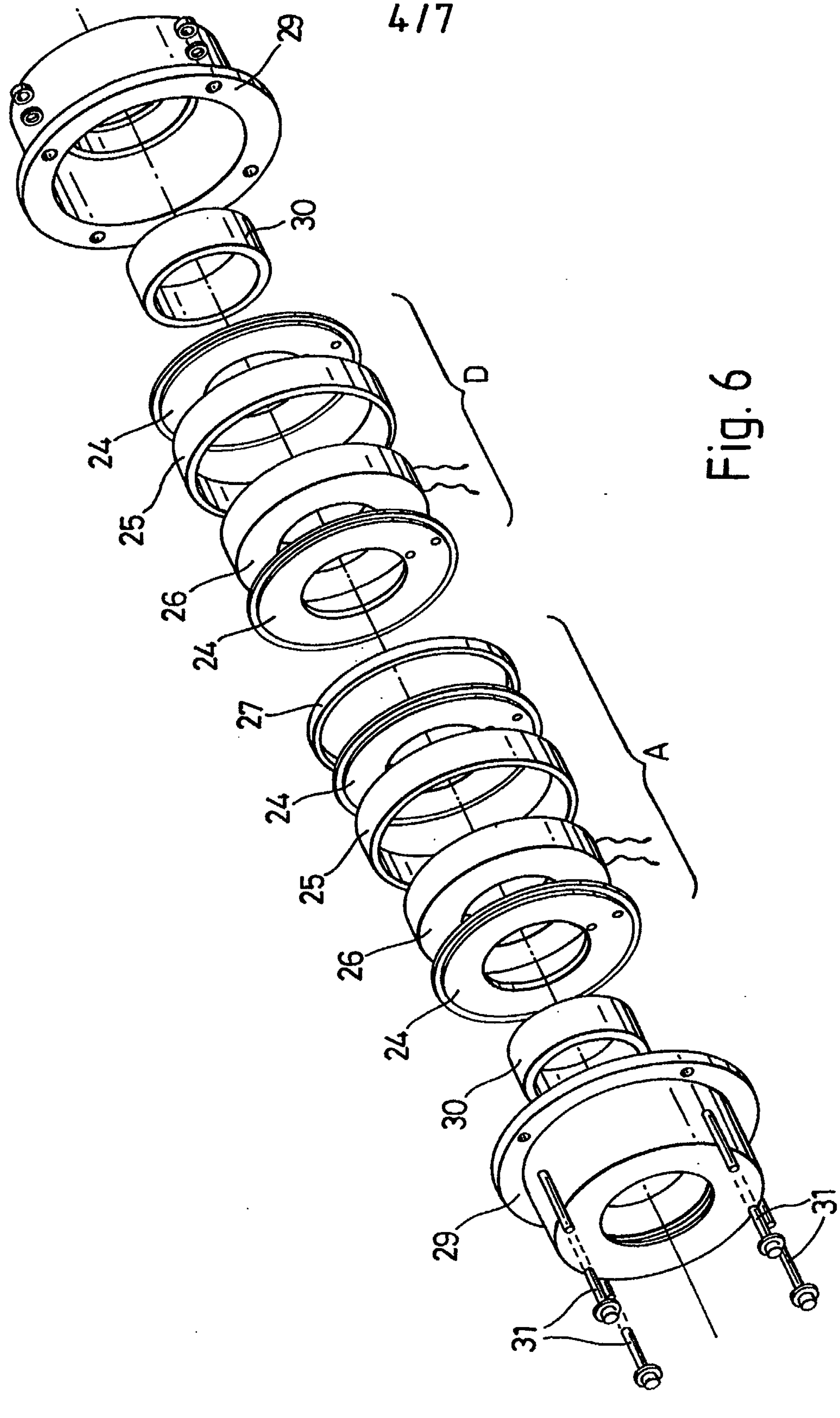



Fig. 6

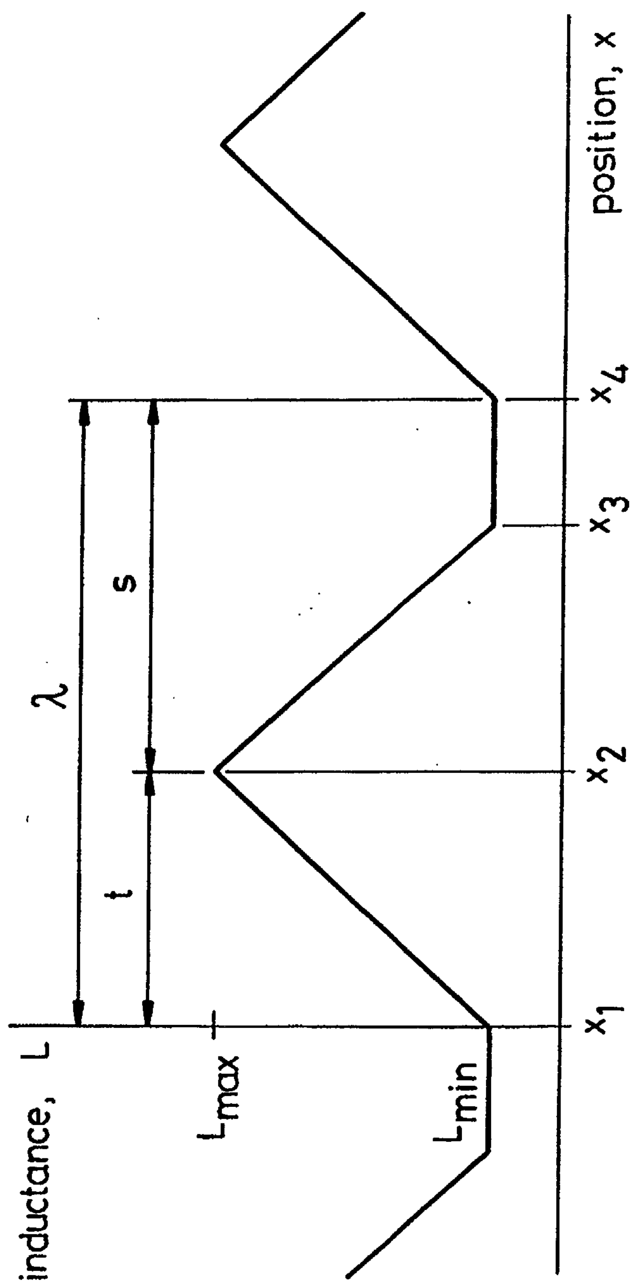



Fig. 7

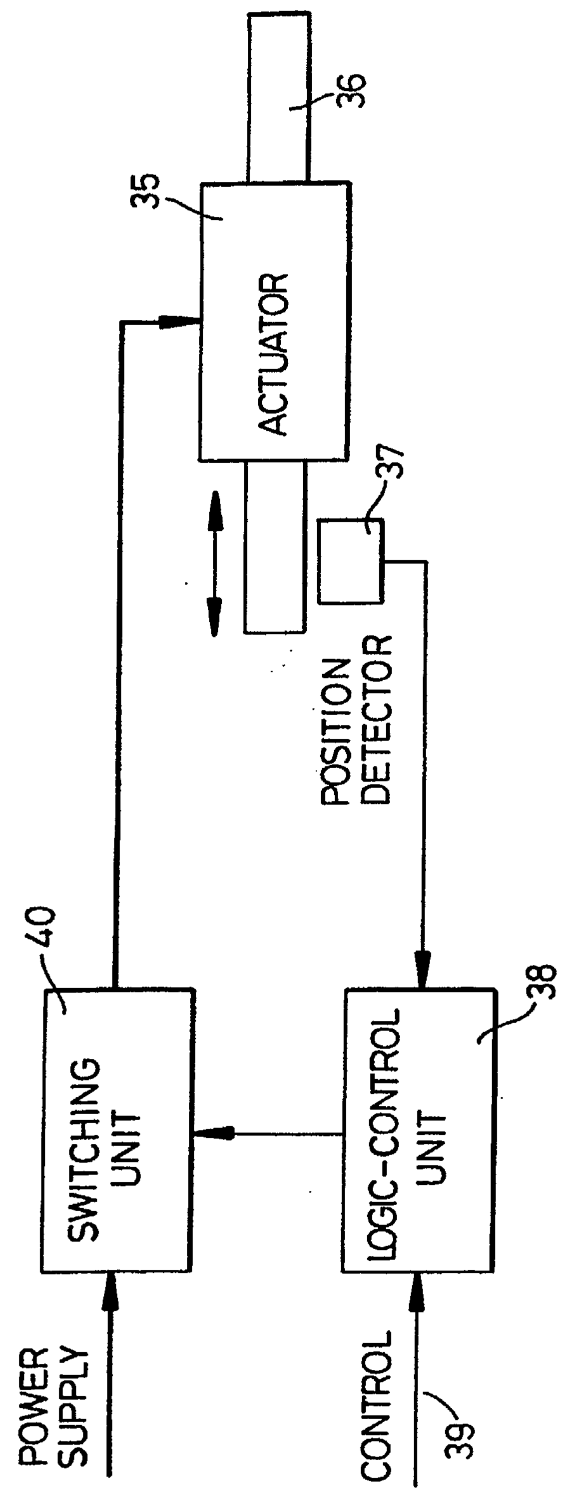
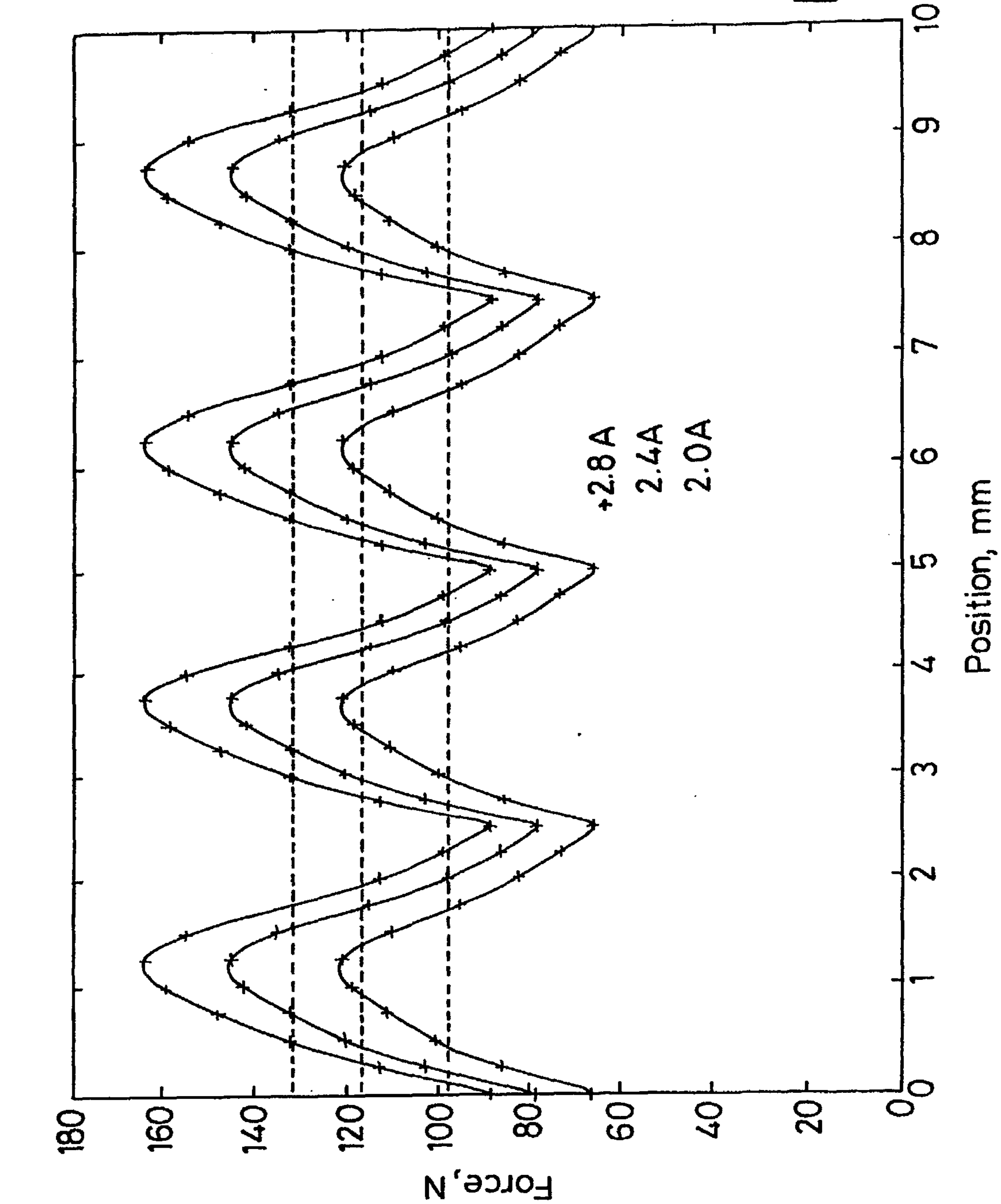

36
35
ACTUATOR
37
POSITION DETECTOR
40
SWITCHING UNIT
LOGIC-CONTROL UNIT
38
POWER SUPPLY
CONTROL
39

Fig. 8

Fig. 9


Force, N
Position, mm
+2.8 A
2.4A
2.0A
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20
40
60
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100
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## INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 94/00906

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC 5 H02K41/03

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)
IPC 5 H02K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

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| Y | see page 4, line 9 - page 6, line 14; figure 1 | 7,8,12 |
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| Y | FR,A,2 172 909 (EVEILLARD J.) 5 October 1973 see page 4, line 26 - line 33; figures 1,2 | 12 |

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 28 July 1994 | -3. 08. 94 |

| Name and mailing address of the ISA | Authorized officer |
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| European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. ( + 31-70) 340-2040, Tx. 31 651 epo nl, Fax: ( + 31-70) 340-3016 | Zoukas, E |

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